Ocean Surface Wave Optical Roughness – Innovative Measurement and Modeling

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LONG-TERM GOALS

This was the final year of the Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program were (1) to examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) to construct a radiance-based SBL model; (3) to validate the model with field observations; and (4) to investigate the feasibility of inverting the model to yield SBL conditions. As part of a multi-institutional research team our goals were to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.
The members of the research team are

Michael Banner, School of Mathematics, UNSW, Sydney, Australia

Johannes Gemmrich, Physics and Astronomy, UVic, Victoria, Canada

Russel Morison, School of Mathematics, UNSW, Sydney, Australia

Howard Schultz, Computer Vision Laboratory, Computer Science Dept, U. Mass., Mass

Christopher Zappa, Lamont Doherty Earth Observatory, Palisades, NY

OBJECTIVES

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure, including very steep nonlinear wavelets and breakers. Traditional descriptors of sea surface roughness are scale-integrated statistical properties, such as significant wave height, mean squared slope (e.g. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and Herbers, 1986). Subsequently, spectral characterisations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al,

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2001, Gemmrich et al., 2008) and microscale breaker crest length spectral density (e.g. Jessup and Phadnis, 2005) have been reported.

Our objective is to provide a more comprehensive description of the physical and optical roughness of the sea surface. We achieve this through the analysis of our suite of comprehensive sea surface roughness observational measurements within the RADYO field program. These measurements cover the fundamental optical distortion processes associated with the air-sea interface. In our data analysis, and complementary collaborative effort with RaDyO modelers, we investigat both spectral and phase-resolved perspectives. These will allow refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

APPROACH

I was working within the larger team (listed above) measuring and characterizing the surface roughness. We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. This team contributed the following components to the primary sea surface roughness data gathering effort in RaDyO:

- <u>polarization camera measurements</u> of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 1), captured at video rates. [Schultz, Zappa]
- <u>co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter</u> data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]
- <u>high resolution video imagery</u> to record whitecap data from two cameras, close range and broad field [Gemmrich]
- <u>fast response, infrared imagery</u> to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]
- <u>air-sea flux package including sonic anemometer</u> to characterize the near-surface wind speed and wind stress [Zappa]

The team provided: detailed analyses of the slope field topography, including mean square slope, skewness and kurtosis; laser altimeter wave height and large scale wave slope data; statistics of whitecap properties, as well as statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the modeling effort focused on using RaDyO data to refine the sea surface roughness transfer function. This includeded the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as micro-breakers.

WORK COMPLETED

My effort in FY11 has been to finalize the characterization of wave breaking and whitecap property statistics extracted from the surface video data obtained during the RaDyO field experiment off Hawaii, August 28 – September 16, 2009 as well as the field experiment in the Santa Barbara channel

during September 4– 28, 2008. In addition, in collaboration with S. Vagle (IOS, Sidney, BC), I estimated total energy dissipation rates from in situ measurements and as inferred from the breaking crest length distribution. (Gemmrich et al 2008). Three manuscripts are under review and a fourth one is in preparation. Results were reported at the General Assembly of the European Geosciences Union and at several workshops and seminars.

RESULTS

Figure 1 below shows a schematic of the instrumentation deployed in the field experiments. Instrumentation and set-up were very similar in the Santa Barbara channel (2008) and the Hawaii (2009) field experiment. Banner/Morison deployed two orthogonal line scanning lidars. The lidars were positioned on the boom so that their intersection point was within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras which were measuring small-scale surface roughness features and breaking waves.

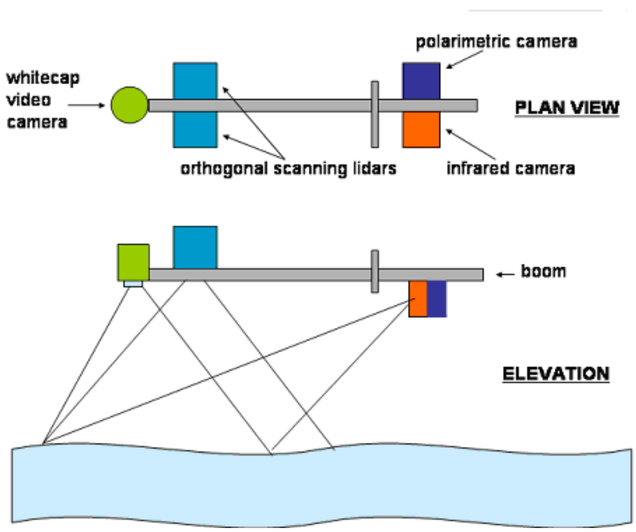

Figure 1. Schematic of the instrumentation set-up deployed from the R/P FLIP starboard boom during the Santa Barbara Channel and Hawaii experiments. The end of the boom was about 9m above the mean water level. The approximate field of view of the various instruments is shown. A second wide angle whitecap video camera was mounted on the crow's nest of R/P FLIP approximately 26m above the water level to image the larger whitecaps.

Zappa deployed his infrared/visible camera system and his environmental monitoring system (sonic anemometer, water vapor sensor, relative humidity/temperature probe, motion package, pyranometer and pyrgeometer). Gemmrich deployed 2 video visible imagery cameras. One camera was mounted on the main boom next to our other instrumentation packages, the second camera was mounted higher up to view larger scale breaking events. Schultz deployed an instrument package located on the boom that includes a polarimetric camera imaging the very small-scale waves.

A wide range of conditions prevailed during the field experiment in Santa Barbara channel (September 4-28, 2008) where the wind speed U_{10} ranged from light and variable, up to 12 m/s. The scale of wave breaking ranged from micro breakers to small-scale breakers with air entrainment to breaking dominant waves with up to 2m wave height. Environmental conditions during the Hawaii experiment (Aug 28 – Sep 16, 2009) were less variable with a nearly fixed wind direction and wind speeds slowly fluctuating between 8 m/s and 12 m/s. Periods of comparable wind speeds resulted in significantly different wave fields (significant wave height, directionality, dominant period) at the two experimental sites.

These data were analysed in terms of breaking crest length density and foam coverage. Results on the breaking crest length distribution $\Lambda(c)$, obtained by the individual tracking method (but not corrected for possible Doppler shifting), are shown in Figure 2. All curves, for both data sets, show the maximum distribution to breaking crests in the intermediate to short wave range (small phase speeds). The small-scale wave breaking was significantly less in the central Pacific Ocean south of Hawaii than in Santa Barbara Channel. The absolute values and the slope of the curves vary significantly throughout the experiments. In Santa Barbara Channel, the overall level of $\Lambda(c)$ fluctuated by more than 1 order of magnitude, roughly following the fluctuations in wind stress. The wave height and wind speed during the Hawaii experiment fluctuated less, and were comparable to the more energetic periods of the Santa Barbara Channel experiment.

Generally, at intermediate wave scales the slopes are less steep than the canonical value $\Lambda(c) \propto c^{-6}$ proposed by Phillips (1985) for the equilibrium range, which is based on assuming comparable importance of wind input, nonlinear spectral transfer and dissipation through breaking. The discrepancy seems to be somewhat larger for the coastal wave field in Santa Barbara channel. The slope decreases with increasing wave age, i.e. the relative importance of large scale breakers increases as the wave field develops. However, we did not find a dependency of $\Lambda(c)$–distribution on the dominant steepness of the wave field $k_p H_s$, as was observed by Thomson et al (2009).

These breaking crest length distributions are solely based on video data. They were also compared to results from the infrared cameras (Zappa) and thereby extended to smaller wave scales.

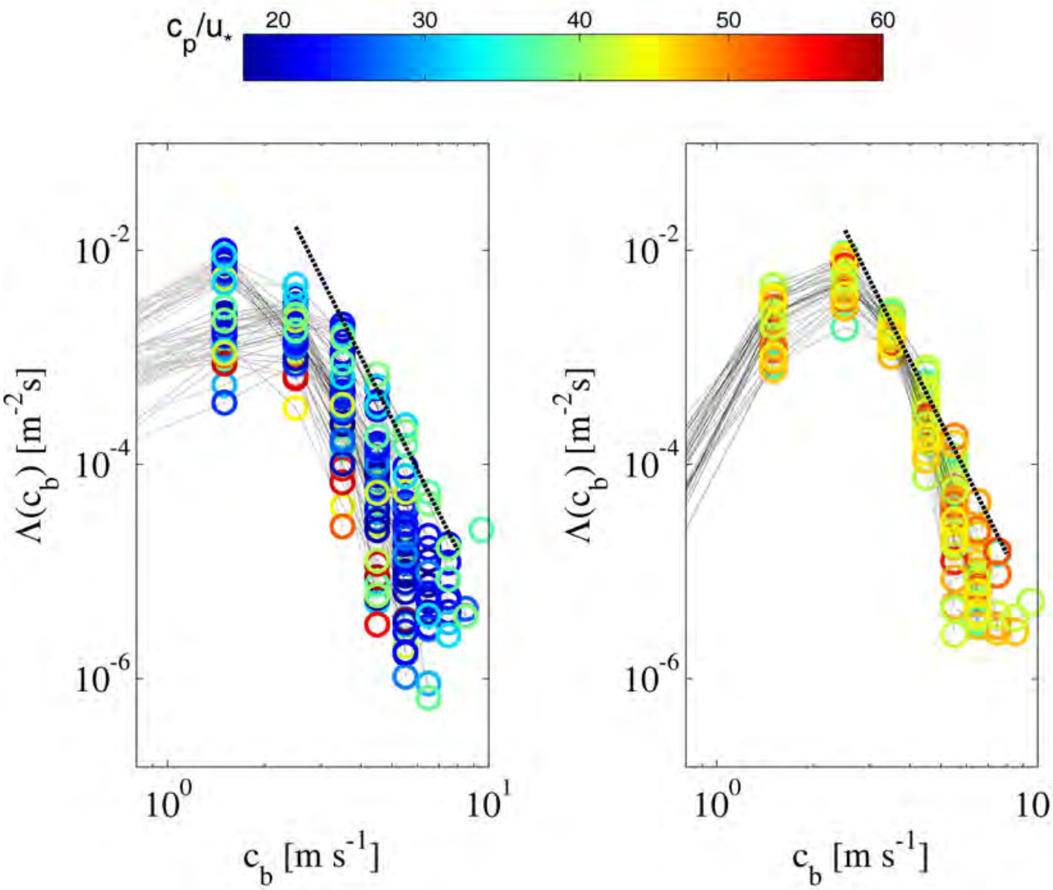

Figure 2: Breaking crest length distributions during the Santa Barbara Channel (left) and Hawaii (right) experiments. The colour coding shows the wave age (c_p/u_*) raging from young wind seas $c_p/u_*\sim20$ (blue) to old wind seas ($c_p/u_*\sim60$) (red). The dashed line represents the c^{-6} dependence predicted by Phillips [1985].

Breaking probabilities, momentum flux and energy dissipation can be extracted from these distributions (see Gemmrich *et al*, 2008). Wave energy dissipation may be estimated from the 5th moment of the crest length distribution $E = b\rho g^{-1}\int c^5\Lambda(c)dc$, where the constant b represents the breaking strength. Comparison with in-situ estimates obtained from high-resolution velocity measurements (similar to Gemmrich 2010) show good agreement between the two methods but suggest that the breaking parameter may differ by a factor of up to 50 between the two locations (Figure 3). This may be related to the strong turbulence suppression by strong heat fluxes during the Hawaii experiment (Vagle et al 2011).

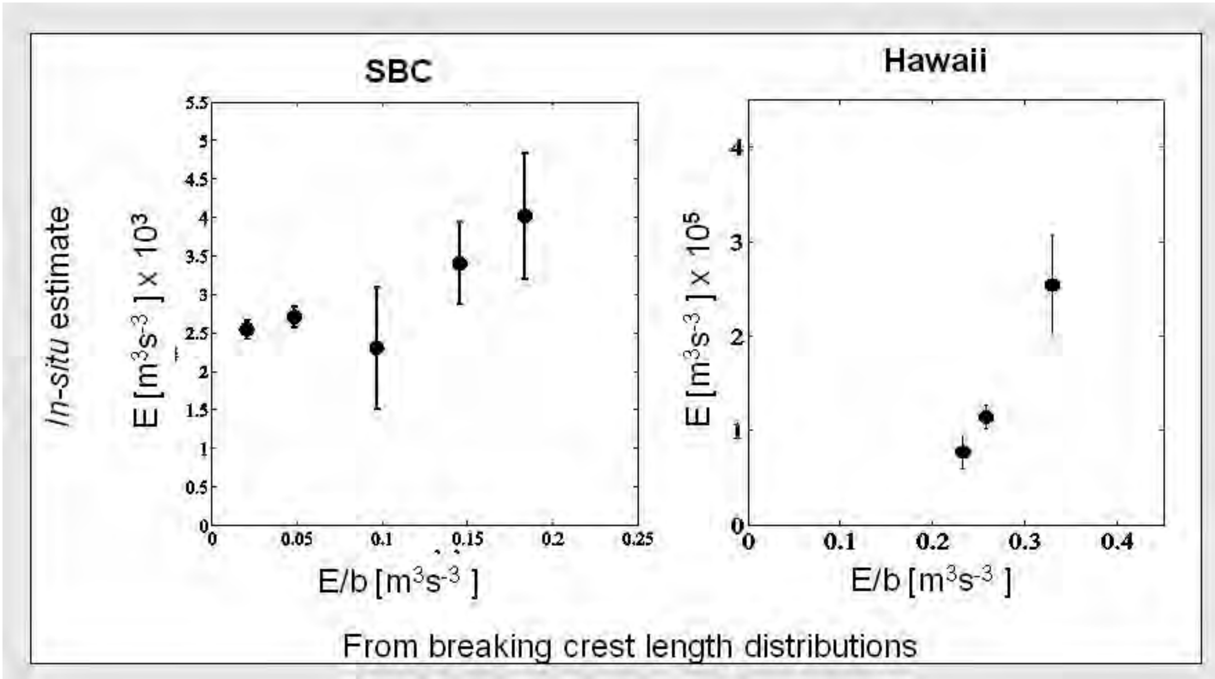

Figure 3: Comparison of wave energy dissipation obtained from in-situ observations and as inferred from the breaking crest length distributions (scaled by the unknown breaking strength parameter b.) Results for the Santa Barbara Channel (left) and Hawaii (right) experiments indicate a difference in the breaking strength parameter b by a factor O(50).

IMPACT/APPLICATIONS

This effort will provide a far more detailed characterization of the wind driven air-sea interface, including wave breaking (whitecaps and microscale breaking). This is needed to provide more complete parameterizations of these processes, which will improve the accuracy of ocean optical radiative transfer models and trans-interfacial image reconstruction techniques.

RELATED PROJECTS

The present project is related to the ONR project **WAVE ENERGY DISSIPATION AND THE DISTRIBUTION OF BREAKING CRESTS**, (ended December 2009), in which Andrew Jessup (APL, UW) was the principal investigator and I was a Co-PI (via subcontract). In this project we looked at breaking crest length distributions and co-located subsurface energy dissipation measurements in a strongly forced wave field in a lake and in Pudget Sound (Thomson *et al*, 2009; Gemmrich, 2010). While the wave scales in RaDyO and the lake/sound experiments are different, common aspects of the data analysis have been transferred to our RaDyO data sets.

REFERENCES

Cox, C.S. and Munk, W.H., 1954: Measurements of the roughness of the sea surface from photographs of the sun glitter. J. Opt. Soc. Am. 44, 838-850.

Gemmrich, J.R., M.L. Banner and C. Garrett, 2008: Spectrally resolved energy dissipation and momentum flux of breaking waves. J. Phys. Oceanogr. 38, 1296-1312.

Gemmrich, J.R, 2010: Strong turbulence in the wave crest region. J. Phys. Oceanogr. 40, 583 – 595

Holthuijsen, L.H., and T.H.C. Herbers, 1986: Statistics of breaking waves observed as whitecaps in the open sea, J. Phys. Oceanogr., 16, 290-297.

Jessup, A.T. and K.R. Phadnis, 2005: Measurement of the geometric and kinematic properties of microsacle breaking waves from infrared imagery using a PIV algorithm. Meas. Sci. Technol. 16, 1961-1969.

Phillips, O.M., 1985: Spectral and statistical properties of the equilibrium range in wind-generated gravity waves, J. Fluid Mech., 156, 505-531.

Phillips, O.M., F.L. Posner and J.P. Hanson, 2001: High resolution radar measurements of the speed distribution of breaking events in wind-generated ocean waves: surface impulse and wave energy dissipation rates. J. Phys. Oceanogr., 31, 450–460.

Thomson, J. and A. T. Jessup, 2009: A Fourier-Based Method for the Distribution of Breaking Crests from Video Observations. J. Atm. Ocean. Tec., 26, 1663 – 1671.

Thomson, J., J. R. Gemmrich and A. T. Jessup, 2009: Energy dissipation and the spectral distribution of whitecaps. Geophys. Res. Let., 36. L11601, doi:10.1029/2009GL038201

Vagle, S, J. Gemmrich, and H. Czerski, 2011: Effect of upper ocean stratification on turbulence and optically active bubbles. J. Geophys. Res.

PUBLICATIONS

Dickey, T., M.-C. Alboussiere, M. Banner, P. Bhandari, T. Boyd, L. Carvalho, G. Chang, Y. Chao, M. Cimono, H. Czerski, M. Darecki, C. Dong, D. Farmer, E. Firing, S. Freeman, J. Gemmrich, P. Gernez, , N. Hall-Patch, B. Holt, J. Hummon, S. Jiang, C. Jones, G. Kattawar, L. Lenain, M. Lewis, Y. Liu, L. Logan, D. Manov, K. Melville, M. Moline, R. Morison, F. Nencioli, S. Pegau, B. Reineman, I. Robbins, R. Röttgers, H. Schultz, D. Siegel, L. Shen, M. Shinki, M. Slivkoff, M. Sokólski, P. Sutherland, F. Spada, N. Statom, D. Stramski, M. Twardowski, S. Vagle, R. Van Dommelen, K. Voss, L. Washburn, J. Wei, H. Wijesekera, O. Wurl, S. Yildiz, Y. You, D. Yue, R. Zaneveld, and C. Zappa, 2011: Recent advances in the study of optical variability in the near-surface and upper ocean. . J. Geophys. Res. [submitted, refereed].

Gemmrich, J.R., M.L. Banner and C. Garrett, 2008: Spectrally resolved energy dissipation and momentum flux of breaking waves. J. Phys. Oceanogr. 38, 1296-1312. [published, refereed]

Gemmrich, J.R, 2010: Strong turbulence in the wave crest region. J. Phys. Oceanogr. 40, 583 – 595 [published, refereed]

Thomson, J., J. R. Gemmrich and A. T. Jessup, 2009: Energy dissipation and the spectral distribution of whitecaps. Geophys. Res. Let., 36. L11601, doi:10.1029/2009GL038201 [published, refereed]

Vagle, S, J. Gemmrich, and H. Czerski, 2011: Effect of upper ocean stratification on turbulence and optically active bubbles. J. Geophys. Res. [submitted, refereed].

Zappa, C.J., M.L. Banner, H. Schultz, A. Corrada-Emmanuel, L.B. Wolff and J. Yalcin, 2008: Retrieval of Short Ocean Wave Slope Using Polarimetric Imaging. Measurement Science and

Technology. Measurement Science and Technology, 19, 055503, pp 13, April 2008 [published, refereed].

Zappa, C.J., J. G. Gemmrich, R. P. Morison, H. Schultz, M.L. Banner, D.A. LeBel, and T. Dickey, 2011: An Overview of Sea State Conditions and Air-Sea Fluxes during RaDyO. J. Geophys. Res. [submitted, refereed]